Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 72 (2015) 399 – 404
Physics Procedia

Conference of Physics of Nonequilibrium Atomic Systems and Composites, PNASC 2015, 18-20 February 2015 and the Conference of Heterostructures for microwave, power and optoelectronics: physics, technology and devices (Heterostructures), 19 February 2015

Thermal regime of high-power laser diodes

V.V. Bezotosnyi[a,b] *, O.N. Krokhin[a,b], V.A. Oleshchenko[b], V.F. Pevtsov[b], Yu.M. Popov[a,b], E.A.Cheshev[a,b]

[a] *National Research Nuclear University MEPhI, Kashirskoe shosse 31, 115409, Moscow, Russia.*

[b] *P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Leninsky prospect 53, 119991, Moscow, Russia.*

Abstract

We discuss the design and application perspectives of different crystal, ceramic and composite-type submounts with thermo-compensating properties as well as submounts from materials with high thermal conductivity for overcoming thermal problem in high-power laser diodes (LD) and improving thermal management of other high-power optoelectronic and electronic semiconductor devices. Thermal fields in high-power laser diodes were calculated in 3 D thermal model at CW operation for some heatsink designs taking into account the experimental dependence of laser total efficiency against pumping current in order to extend the range of reliable operation up to thermal loads 20-30 W and corresponding output optical power up to 15-20 W for 100 μm stripe laser diodes.

Keywords: *diode lasers; thermal conductivity; total efficiency; diamond submounts.*

* Corresponding author. Tel.: +7-495-132-6126; fax: +7-495-135-8589
E-mail address: victorbe@sci.lebedev.ru

doi:10.1016/j.phpro.2015.09.071

Introduction

Typical total efficiency for modern high-power laser diodes (LD) is around 65 % and the output power is up to 10 W CW. Many laboratories and some commercial companies are on the way to insure the reliable output power twice more, up to 20 W from 100 μm wide stripe. Among them Bezotosnyi et al. (2009), Crump et al. (2012), Yongkun et al. (2012), Yanson et al. (2012). To make the next step towards the increase of reliable output power we need to increase the efficiency of heat transfer from the laser active region to the basic heat-spreading element. The commercially available laser diodes insure reliable CW operation at quite high thermal loads around 3 kW/cm ^{2}, but the potential power range of this devices is far from the limit values. An extremely high density of heat sources inside the active layer of laser heterostructure is the fundamental item based on the fact that radiative recombination of injected carriers takes place inside the nanoscale layer, that's why for a typical commercially available 100 μm wide stripe laser operating at 10W, the density of heat generated inside the active layer is close to 3 GW/ cm ^{3}, which is the record value for semiconductor optoelectronic devices. We should realize that extending the reliable optical power range up to 20 W is associated with heat density raise in active region up to 10 GW/ cm ^{3}.

General considerations

Clearly, in order to increase twice the value of the output power (from 10 W to 20 W CW) and insure reliable operation at such power, we need to expand the linear range of W/A characteristic up to at least twice more pumping current. Due to quadratic dependence of Ohmic loss of the chip against the pumping current, the value of total efficiency decreases at high pumping level which is obvious from a simplified formula of Bezotosnyi et al. (1997) for total efficiency (1):

$$\eta_{tot} = \eta_d \frac{(I - I_{th})E_g}{I[U_{th} + R_s(I - I_{th})]} \tag{1}$$

Where I is the pumping current; I_{th}, the threshold current; E_g, the bandgap ; U_{th}, the voltage at threshold; R_s,, series resistance; η_d, differential efficiency . As a result, if we want to increase the output optical power twice, from 10 to 20 W CW , at typical values of thermal resistance Rs around 40 mOhms, we need to remove at least 3 times more heat flux, because of higher thermal load according to a decrease of total efficiency at high pumping currents.

Thermal load P_{therm} is presented in (2) as a dependence against total efficiency η_{total}. The value of thermal load around 30 W correspond to the heat source density up to 10 GW/ cm ^{3} and thermal fluxes around 10 kW /cm ^{2} which are extremely high .

$$P_{therm} = I \cdot U\,(1 - \eta_{tot}) \tag{2}$$

Thermal management under such high levels of heat source and heat flux density and further desirable increase of these parameters to insure reliable operation regime must be guaranteed at quite small permissible temperature drop around 30 ° C between the active layer and heat – removing element. The 30 º C temperature drop is based on our experimental data regarding the investigation of long-term reliability tests of different high-power laser diode designs operating at different wavelengths in the range 800-1060 nm. The technical decision of thermal problem requires application of new materials with very high thermal conductivity and new methods for effective heat transfer. The maximum of total efficiency is defined according to Bezotosnyi et al. (1997) as an extremum of the function in expression (1) .

$$\eta_{tot}^{\max} = \frac{\eta_d J E_g}{I_{\max}(U_{th} + R_s J)} \tag{3}$$

$$J = \sqrt{I_{th} U_{th} / R_s} \quad I_{\max} = I_{th} + J \qquad (4)$$

Correspondingly to (3) and (4), the increase of total efficiency peak value may be achieved by an increase of differential efficiency and a decrease of the series resistance. The decrease of series resistance is even more valuable for high –power operation since this also moves the position of total efficiency peak to higher pumping currents .

The problem of thermo-elastic strain in laser diodes

The technology of high-power diode lasers together with the heat transfer problem involves the problem of matching the thermal expansion coefficients inside the hybrid design of laser diode chip assembled on the heat-removing element. The problem is defined by sufficient difference of thermal and mechanical properties of semiconductor and heat-removing materials. This is a serious problem of thermo-elastic strain in hybrid assemblage. Thermal expansion coefficient of diamond at 300K is $1 \cdot 10^{-6}$ K^{-1}, copper, $16.7 \cdot 10^{-6}$ K^{-1}, semiconductor around $6\ 10^{-6}$ K^{-1}. The problem of thermo-elastic strain in most cases can be solved by thermo-compensators from crystal, ceramic or composite material used as an intermediate layer between the basic copper heat-removing element and semiconductor laser crystal. Commonly used thermo-compensators are produced from dielectrics AlN, BeO, SiC, as well as from current conducting composites CuW and CuMo. The listed below thermo-compensators exhibit sufficiently lower, as compared to copper, thermal conductivity in the range 150-250 W/m · K and that's why cannot solve thermal problem and insure reliable operation of high-power LD at the output power levels more than 10 W CW .

Diamond and diamond-based materials for high-power LD submounts

Diamond and diamond-based composites are among the most perspective candidates for high-power LD submounts. The main advantage of pure diamond is the highest thermal conductivity among known materials, up to 2400 W/ m·K for special type pure diamond and even up to 3600 W/ m·K for isotopically clean material.

The key question regarding metallization of massive diamond and diamond grains concerns the physical mechanism of heat transfer at diamond-metal boundary because diamond, as dielectric, have phonon-type heat transfer different from electron-type mechanism in metals. In article of Meilakhs et al. (2013) to clear up situation a new model of heat transfer at the boundary diamond-copper has been proposed. The main result of the model shows that high frequency oscillations in dielectric can propagate inside the metal, but are quickly damped, the energy transfer takes place in the thin layer close to the metal boundary.

At the same time diamond have an important disadvantage because of the large difference in thermal expansion coefficient with semiconductor heterostructure. To overcome this, a diamond-copper composite has been proposed.

In experimental work of Abyzov et al. (2012) several problems of copper-diamond composites are listed, among them the non-wetting of diamond grains by copper melt, diamond grains destruction at high temperature and pressure, quite large critical diamond grain size around 11 - 35 µm, necessary to increase thermal conductivity of composite above copper matrix, etc. All together the listed features of copper-diamond composite not only decrease it thermal conductivity, but also causes problems for precise mechanical treatment under submounts manufacturing.

The highest composite thermal conductivity at optimal grain size around 100 µm was 600 W/ m · K. Processing of a composite with large grain size into submounts qualified for LD assembling is a serious problem because diamond grains are hard and the copper matrix is soft, the usual mechanical polishing cannot keep the stable grains position resulting in composite surface destruction. Appropriate processing needs quite expensive non-destructive processing methods, such as ion milling. Anyway Sumitomo managed to produce composite suitable for LD assembling with thermal conductivity around 1000 W/ m·K , so this is a question of high technology.

An important item is the price of the submounts. For massive synthetic diamond material, as well as for high-quality CVD diamonds, it is more than 1000 USD/cm^3. The cost of diamond processing (cutting, polishing, thermal management , etc.) involved in production of diamond submounts suitable for LD assembling is even much higher since an appropriate high surface roughness and edge quality are necessary for efficient heat transfer via LD chip – submount interface. Metallization technology for diamond submounts, particularly based on TiPtAu magnetron sputtering, is also quite expensive, finally the cost of ready submounts at the moment is too high for mass production. At the same time, thermal modeling results for LD bonded via diamond submounts gives us the good perspectives for extending the reliable operation to higher power range.

3 D Thermal modeling

We have calculated the temperature distributions in 3D thermal model based on the measured parameters of LDs. The details of heat flow inside the laser chip and submount are clear from Fig. 1. Due to high thermal parameters of diamond, the active region is overheated only by 10 degrees, the submount is cool, but the LD substrate is warm as it thermal conductivity is quite low. We published our experimental results for LDs assembled via polycrystalline diamond submounts particularly in article of Ashkinazi et al. (2012), the best LD sample operated at 12 W around 50 hours. Sufficiently more power was expected for such LDs at announced submount thermal conductivity.

More precise measurements showed that real thermal conductivity of diamond submounts used in that work was much less, it degraded after thermal treatment and metallization and did not exceed 600 - 800 W / m · K for ready samples. Thermal parameters for diamond and composite submounts are clear from the results of our calculations recently published in two articles of Bezotosnyi et al. (2014).

Conclusions

Our experimental and 3D thermal modeling results confirm that diamond or diamond – copper submounts with optimal design can be used to extend the reliable operation range of high-power laser diodes up to thermal loads 30 W , which corresponds to LD output power around 20 W CW and the temperature of basic copper F-mount plane 20 °C . As concerns the heat transfer demands, to insure reliable operation at 20 W, thermal conductivity 1200 –

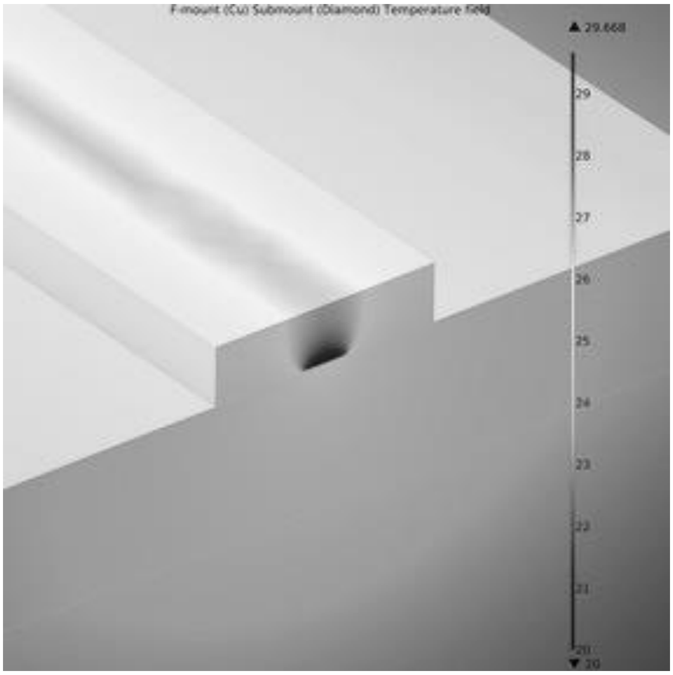

Fig.1. Calculated heat flow at LD chip and diamond submount with 1200 W/ m·K assembled at copper F-mount, basic plane at 20 ºC, thermal load 10 W CW.

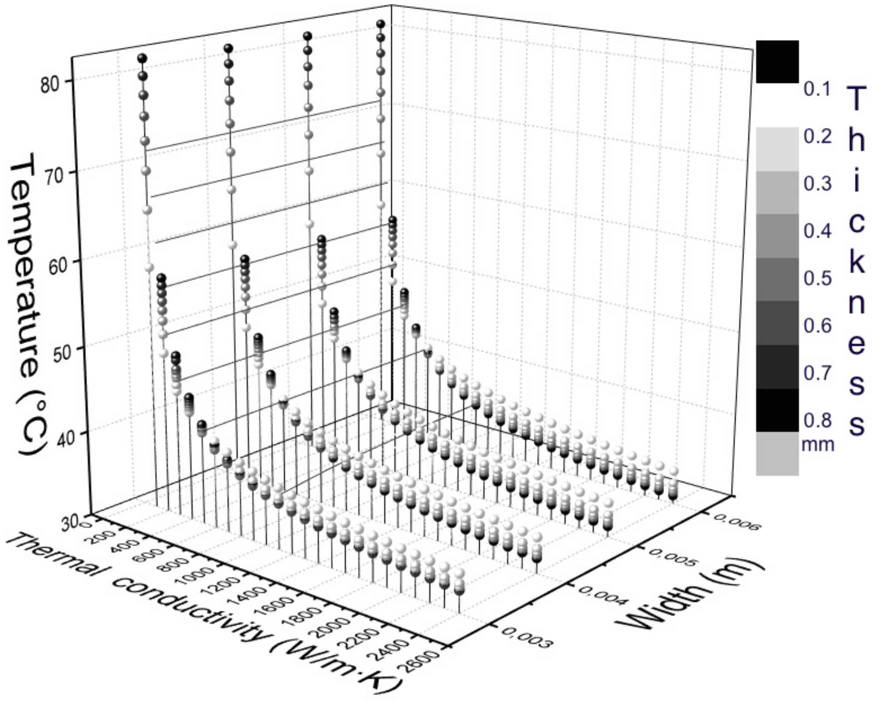

Fig. 2. Calculated average temperature of LD active layer against submount thermal conductivity, width and thickness. Assembling on copper F-mount, thermal load 20 W CW.

- 1400 W / m·K of diamond or composite copper – diamond submounts is quite enough and this is attractive for contemporary synthetic poly-diamond technology and price considerations. Some additional efforts must be applied for further development of synthetic diamond materials and composite materials as well as for processing technology of these materials, particularly of comparably cheap CVD polycrystalline synthetic diamond and diamond – copper composite in order to increase thermal conductivity, thermal stability, decrease the price of basic material and its processing and introduce such submounts in mass production of high-power LD and LD arrays.

Acknowledgements

This work was performed in National Research Nuclear University MEPhI under the Agreement № 14.575.21.0047 with Ministry of Education and Science of Russian Federation, the unique identification number of applied scientific research RFMEFI57514X0047. The authors take up the following posts in the University : O. N. Krokhin, head of the Department; Yu. M. Popov, professor ; V.V.Bezotosnyi, associated professor, E.A. Cheshev, associated professor.

References

Abyzov, A.M., Kidalov, S.V., Shakhov, F.M., 2012, Physics of the Solid State , **54**, 1, p. 210.
Ashkinazi, E.E., Bezotosnyi, V.V., Bondarev, V.Yu., Kovalenko, V.I., Konov, V.I., Krokhin, O.N., Oleshchenko, V.A., Pevtsov, V.F., Popov, Yu.M., Popovich, A.F., Ral'chenko, V.G., Cheshev, E.A., 2012, Quantum Electronics **42** (11) p. 959.
Bezotosnyi, V.V., Kumykov, Kh.Kh., Markova, N.V., 1997, Quantum Electronics **24** (6) p. 481.
Bezotosnyi, V.V., Bondarev, V.Yu., Krokhin, O.N., Mikaelyan, G.T., Oleshchenko, V.A., Pevtsov, V.F., Popov, Yu.M., Cheshev, E.A., 2009, Quantum Electronics **39** (3) p. 241 - 243.
Bezotosnyi, V.V., Krokhin, O.N., Oleshchenko, V.A., Pevtsov, V.F., Popov, Yu.M., Cheshev, E.A., 2014, Quantum Electronics **44** (2), p. 145.
Bezotosnyi, V.V., Krokhin, O.N., Oleshchenko, V.A., Pevtsov, V.F., Popov, Yu.M., Cheshev, E.A., 2014, Quantum Electronics,**44** (10), p. 899.
Crump, P., Blume, G., Paschke, K., Staske, R., Pietrzak, A., Zeimer, U., Einfeldt, S., Ginolas, A., Bugge, F., Häusler, K., Ressel, P., Wenzel, H., Erbert, G., 2012. 20W continuous wave reliable operation of 980nm broad-area single emitter diode lasers with an aperture of 96um.

Proceedings of SPIE 7198, 719814-1.
Meilakhs, A.P., Eidelman, E. D., 2013. New model of heat transport across the metal-insulator interface by the example of boundaries in a diamond-copper composite. JETP Letters 97 (1), 38-40.
Sin, Y., LaLumondiere, S. D., Presser, N., Foran, B. J., Ives, N. A., Lotshaw, W. T., Moss, S. C., 2012. Physics of failure investigation in high-power broad-area InGaAs-AlGaAs strained quantum well lasers. Proceedings of SPIE 8241, 824116-1.
Yanson, D., Cohen, S., Levy, M., Shamay, M., Geva, S., Berk, Y., Tesler, R., Klumel, G., Rappaport, N., Karni, Y., 2012. Multi-spectral investigation of bulk and facet failures in high-power single emitters at 980 nm. Semiconductor Laser Conference (ISLC) 23rd IEEE International, 99-98.